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ALTITUDE PERFORMANCE OF A FULL-SCALE TURBOJET

ENGINE USING PENTABORANE FUELS (4)

By James W. Useller, Warner B. Kaufman, and William L. Jones

Lewis Flight Propulsion Laboratory Cleveland, Ohio

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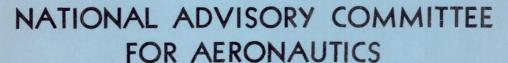
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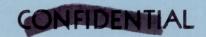


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ALTITUDE PERFORMANCE OF A FULL-SCALE TURBOJET

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SUMMARY

A brief investigation of the use of 85 percent pentaborane - 15 percent hydrocarbon fuel (JP-4 fuel) and of 100 percent pentaborane fuel mixtures was conducted in a full-scale turbojet engine at a simulated altitude of 50,000 feet and a flight Mach number of 0.8. A total of 120 pounds of pentaborane was used, which limited the test period to about 11 minutes duration.

A tabular and graphical presentation has been made of both the standard engine performance parameters of net thrust, specific fuel consumption, and engine total-pressure ratio, as well as the engine component performance. Subsequent to operation of the engine with the pentaborane fuels, the engine was operated with JP-4 fuel to study the dissipation of the boric oxide deposits and the rate of return of the engine to the normal performance level.

INTRODUCTION

The range of operation of an aircraft can be shown to be a direct function of the heat released per pound of fuel consumed by the propulsion system. Assuming similar efficiency of combustion, the substitution of a fuel with an increased heat of combustion will result in a proportionate increase in the range of operation or a decrease in the specific fuel consumption.

The boron hydride high-energy fuels produce heat releases approximately 50 percent greater per pound of fuel than hydrocarbon fuels currently in use. Of the boron hydrides under consideration, pentaborane has been shown to exhibit promise as a turbojet-engine fuel. Therefore, full-scale turbojet-engine tests were undertaken in an NACA altitude test chamber (ref. 1). The limited availability of pentaborane precluded operation with pentaborane fuel for long periods of time. The

investigation of reference 1 was limited to concentrations of pentaborane in JP-4 fuel of less than 42 percent because previous small-scale tests had shown that serious operational difficulties could be presented by the boric oxide deposits of higher concentration fuels. The effect of the oxide deposits was found to be comparatively innocuous at the concentrations investigated and further studies have been made using 85 and 100 percent pentaborane mixtures. The results of the later tests are reported herein.

The engine was operated at conditions simulating flight at an altitude of 50,000 feet and a Mach number of 0.8. This investigation was conducted at the request of the Bureau of Aeronautics, Department of the Navy, as a part of Project Zip.

The data presented herein include the standard engine performance parameters of net thrust, specific fuel consumption, and engine total-pressure ratio that reflect the performance available from the use of pentaborane as a fuel. The influence of the boric oxide deposits from the high-concentration pentaborane fuels on engine component performance is presented. The combustion system used for pentaborane fuel had previously been developed in single-combustor tests by the General Electric Company.

Subsequent to operation of the engine with the pentaborane fuels, the engine was operated with JP-4 fuel to study the dissipation of the boric oxide deposits and the rate at which the engine performance approached normal values. These data are also presented herein.

APPARATUS

Engine. - A schematic sketch of the engine used in this investigation is shown in figure 1. The engine is a standard production model and contains a 12-stage axial-flow-type compressor, eight tubular combustion chambers, and a single-stage turbine. A variable-area exhaust nozzle permitted operation at the maximum allowable turbine-outlet gas temperature, 1250° F, and rated engine speed. The standard engine configuration was modified in that two special fuel nozzles of the atomizing type were installed in each of the combustion chambers as is shown in figure 2, and the turbine shroud was modified as is shown in figure 3 to increase the turbine tip clearance from the leading edge to the trailing edge of the turbine blade.

Fuel system. - A schematic diagram of the fuel system used with the pentaborane fuel is shown in figure 4. The pentaborane fuel was pressurized with helium forcing it from a suspended tank through metering devices into the special fuel nozzles. Provision was made for purging the pentaborane fuel lines with JP-4 and helium to reduce the handling hazards.

Fuels.	- Pentaborane fuel of approximately 99 percent purity was
	the Bureau of Aeronautics for this investigation. The
pentaborane	fuel properties are as follows:

Formula weight									. 63.17
Melting point, OF									52
Boiling point, of at 760 mm Hg									136
Heat of combustion, Btu/lb									29,127
Specific gravity, 32° F									. 0.644
Stoichiometric fuel-air ratio									0.0764
Pounds of B203 per million Btu	•								94

Boric oxide, B203, exhibits the following melting points:

Crystalline,	0	F													. 842	2
Vitreous, OF															1070	0

Instrumentation. - Location of the instrumentation stations and the instrumentation at each station are shown in figure 1. The total-pressure probes downstream of the combustor were of the purge type to prevent contamination and plugging by the boron oxide. Engine air flow was measured at the engine inlet, station 1. The fuel flow was measured by Potter flow meters and the engine thrust was measured with a null-type thrust cell.

PROCEDURE

The duration of the pentaborane fuel operation was approximately ll minutes and was limited by the small quantity of fuel available. Special operational and data-recording procedures were necessary. The procedure followed was to establish the engine operating condition with the use of JP-4 fuel and then transfer to the pentaborane fuel. Following approximately 3 minutes operation with 85 percent pentaborane - 15 percent JP-4 fuel mixture, the engine was operated for 6 minutes on 100 percent pentaborane. Engine speed and exhaust-gas temperature were held nearly constant by varying the fuel flow and exhaust-nozzle area. Data were taken at 15-second intervals. In so far as possible, the engine was held at constant operating conditions during the data-recording cycle.

Following the pentaborane fuel operation, the engine was shut down and inspected for boric oxide deposition. After this inspection, the engine was operated with JP-4 fuel to determine the rate of dissipation of the boric oxide deposits.

Data were adjusted to a condition which corresponds to a simulated altitude of 50,000 feet and a flight Mach number of 0.8. In addition to the application of the temperature and pressure adjustments required for NACA standard altitude conditions, the engine total-temperature ratio $\rm T_9/T_1$ was adjusted to establish a constant $\rm T_9/T_1$ equal to 3.3. The unadjusted data as taken during the investigation are presented in tabular form in table I. Appendix A contains a list of symbols used herein, and appendix B demonstrates the method of calculation employed.

DATA PRESENTATION

Engine and component performance. - The standard engine performance parameters of net thrust, specific fuel consumption based on net thrust, and engine total-pressure ratio are shown in figure 5. The data shown at zero time are for operation with the conventional hydrocarbon fuel JP-4. The remaining data shown are for operation with an 85 percent pentaborane - 15 percent JP-4 mixture and with pure pentaborane fuel. Performance during the period of transition from one fuel to the other has been omitted.

The effect of operation with the high-concentration pentaborane fuels on the combustor and turbine performance is presented in figure 6. A cross plot of the data of figure 5 is shown in figure 7, where the change in specific fuel consumption is shown as a function of the pentaborane concentration in a hydrocarbon fuel. The data for concentrations up to 42 percent were taken from reference 1. The data for concentrations of 85 percent and pure pentaborane are from this investigation and are based on the minimum specific fuel consumptions encountered.

Boric oxide deposits. - Following the ll minutes of operation of the engine with the 85 percent mixture and pure pentaborane, an inspection of the engine component parts revealed the deposits shown in figure 8. The nature of the vitreous deposits can be best seen in figures 8(c) and (d). Approximately 120 pounds of pentaborane were consumed, resulting in about 330 pounds of boric oxide. Of course, an appreciable quantity of this formation was carried off by the exhaust-gas stream.

Deposit dissipation. - Operation of the engine with JP-4 fuel subsequent to the use of the pentaborane fuels dissipated the boric oxide deposits, and the engine performance approached its normal value. The rate of dissipation and return to normal performance are shown in figure 9. Following 80 minutes of operation with JP-4 fuel, visual inspection revealed that only very moderate amounts of boric oxide remained on the engine components, as may be seen in figure 10.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 9, 1954
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APPENDIX A

SYMBOLS

The following symbols are used in this report:

- A area, sq ft
- Fd thrust system scale reading, lb
- F, jet thrust, lb
- Fn net thrust, lb
- f fuel-air ratio
- g acceleration due to gravity, ft/sec2
- h enthalpy, Btu/lb
- hf lower heating value of fuel, Btu/lb
- K thermodynamic constant
- M Mach number
- m mass flow, slugs/sec
- N engine speed, rpm
- P total pressure, lb/sq ft
- p static pressure, lb/sq ft
- T total temperature, OR
- V inlet velocity, ft/sec
- Wa air flow, lb/sec
- Wf fuel flow, lb/hr
- γ ratio of specific heats
- δ_a ratio of engine-inlet total pressure P_1 to P at $M_1 = 0.8$; altitude, 50,000 ft

- θ_a ratio of engine-inlet total temperature T_1 to T at $M_1 = 0.8$; altitude, 50,000 ft
- η efficiency

Subscripts:

- a air
- b combustor
- c compressor
- cl compressor 12-stage leakage flow
- m fuel manifold
- mix pentaborane JP-4 fuel mixture
- t turbine
- tl turbine cooling
- O free stream
- l engine inlet
- 3 compressor outlet
- 4 turbine inlet
- 5 turbine outlet
- 9 exhaust-nozzle inlet

APPENDIX B

METHOD OF CALCULATION

The values used for specific heat at constant pressure, ratio of specific heats, and various enthalpies for air and hydrocarbon products of combustion were obtained from reference 2 and for pentaborane, from reference 3.

Engine air flow. - The compressor-inlet air flow was determined from total and static pressure and temperature measurements at the engine inlet, station 1. The compressor and turbine leakage was measured at two instrumented stations on the compressor and one on the turbine. Therefore,

$$W_{a,3} = W_{a,1} - W_{a,cl_1} - W_{a,cl_2} - W_{a,tl,1}$$

Thrust. - The jet thrust determined from the thrust-system measurements was calculated from the following equation:

$$F_j = F_d + A_s(p_l - p_0)$$

where As is the area of the seal around the engine inlet.

The net thrust was determined by subtracting the inlet momentum from the jet thrust:

$$F_n = F_j - \frac{W_{a,1}V_0}{g}$$

When the test conditions deviated from the desired simulated flight conditions (M_0 = 0.8; altitude, 50,000 ft), the data were adjusted by the appropriate values of θ_a and δ_a .

Combustion efficiency. - The combustion efficiency of the engine combustor was defined as

$$\eta_{b} = \frac{(1 + f)h_{a,9} - h_{a,1}}{fh_{c}}$$

The JP-4 fuel combustion efficiency was determined from

$$\eta_b = \frac{h_a \int_{T_1}^{T_9} + f\left(\frac{A_m + B}{m + 1}\right) \int_{T_m}^{T_9}}{fh_f}$$

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where $\frac{A_m + B}{m+1}$ accounts for the difference between the enthalpy of carbon dioxide and water vapor in the burned mixture and the enthalpy removed from the air by their formation (ref. 2). The temperature of the fuel prior to entry into the engine is T_m .

Pentaborane. - Pentaborane fuel combustion efficiency was calculated as follows:

$$\eta_b = \frac{(h_9 - h_{a,1}) - f(K)}{fh_f}$$

where hg and K are from NACA unpublished data based on thermodynamic data of reference 2.

Turbine efficiency. - The turbine efficiency was calculated from

$$\eta_{t} = \frac{1 - \frac{T_{9}}{T_{4}}}{1 - \left(\frac{P_{5}}{P_{4}}\right)^{\gamma}}$$

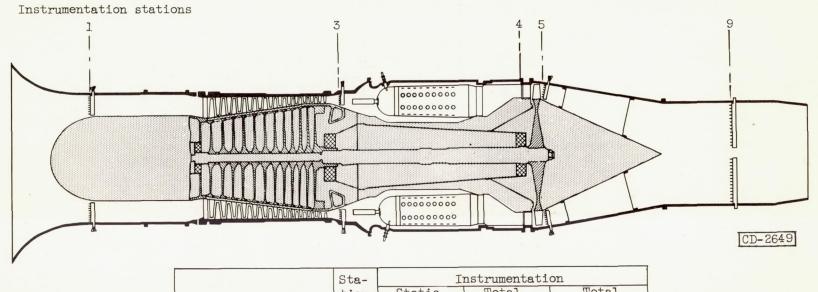
A 5-percent total-pressure loss in the tailpipe was assumed as determined from previous tests.

REFERENCES

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- 2. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)
- 3. Huff, Vearl N., Gordon, Sanford, and Morrell, Virginia E.: General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA Rep. 1037, 1951. (Supersedes NACA TN's 2113 and 2161.)

TABLE I. - TABULATED ENGINE PERFORMANCE DATA

Run	1	Fuel	Time of	Altitude	Engine-	Engine-	Compressor	Compres-	Combustor	Exhaust-	Exhaust-		Engine-	Compressor	Turbine	Engine	Jet	Net
	JP-4, percent by weight	Penta- borane, percent by weight	operation, min	ambient pressure, po, 1b sq ft abs	inlet total pressure, P1, 1b sq ft abs	inlet total temper- ature, T, oR	outlet total pressure, P3, 1b sq ft abs	sor outlet total tempera- ture, T ₃ , o _R	outlet total pressure, P4, lb sq ft abs	nozzle inlet total pressure, Pg, lb sq ft abs	nozzle inlet total temper- ature, Tg, oR	speed, N, rpm	inlet air flow, Wa,1, lb/sec	outlet air flow, Wa,3, lb/sec	outlet air flow, Wa,5, lb/sec	fuel flow W _f , lb/hr	thrust, Fj, 1b	thrust, Fn, 1b
1 2 3 4 5	100 100 100 100 100	0		334 336 336 336 336 336	423 423 423 420 420	520 520 520 520 520 520	2224 2227 2227 2235 2231	922 921 922 922 922	2107 2110 2110 2119 2114	783 782 786 786 784	1687 1692 1692 1692 1691	7792 7799 7797 7799 7801	19.53 19.53 19.53 19.45 19.45	19.07 19.07 19.07 18.99 18.99	19.19 19.19 19.19 19.11 19.11	1258 1258 1253 1253 1253	1279 1276 1279 1274 1272	879 880 883 886 884
6 7 8 9 10	100 16.20 14.93 15.64 15.65	0 83.80 85.07 84.36 84.35	0 2.5 2.7 3.1 3.4	336 333 338 340 343	420 419 419 420 420	520 520 520 520 520 521	2232 2196 2245 2207 2194	922 909 925 932 920	2115 2079 2128 2091 2078	783 753 754 751 756	1660 1724 1720 1695 1700	7801 7794 7961 7803 7704	19.45 19.43 19.68 19.45 19.18	19.00 18.98 19.21 18.99 18.71	19.12 19.10 19.33 19.11 18.83	1253 938 931 889 888	1260 1267 1271 1238 1222	872 874 885 860 856
11 12 13 14 15	15.56 15.37 15.37 15.09	84.44 84.63 84.63 84.91	3.7 4.0 4.3 4.6 4.9	340 340 340 340 340 333	423 423 420 423 419	520 521 520 521 520	2180 2174 2192 2233 2281	915 914 916 917 922	2065 2059 2077 2117 2164	752 742 741 756 769	1697 1688 1697 1764 1722	7685 7740 7748 7854 7985	19.29 19.27 19.45 19.52 19.68	18.83 18.82 18.99 19.06 19.21	18.95 18.93 19.11 19.18 19.33	887 885 885 888 861	1230 1217 1230 1273 1295	849 836 852 887 897
16 17 18 19 20	0	100	5.2 5.5 5.8 6.1 6.5	334 340 336 340 334	420 420 420 423 423	521 521 521 521 521	2233 2223 2206 2213 2211	936 926 922 917 914	2117 2107 2091 2099 2097	748 752 746 749 745	1776 1715 1710 1726 1722	7819 7788 7726 7733 7772	19.43 19.44 19.19 19.27 19.27	18.97 18.98 18.75 18.80 18.83	19.09 19.10 18.87 18.92 18.95	813 804 804 808 825	1277 1245 1232 1236 1246	884 866 849 855 851
21 22 23 24 25			6.8 7.1 7.4 7.7 8.1	343 343 347 347 347	420 422 420 423 423	521 521 520 521 521	2200 2192 2212 2224 2228	920 917 916 916 919	2085 2078 2098 2111 2115	732 734 735 743 740	1705 1720 1720 1726 1732	7722 7696 7713 7742 7744	19.44 19.24 19.21 19.27 19.27	19.00 18.78 18.74 18.82 18.80	19.12 18.90 18.86 18.94 18.92	813 827 837 859 861	1219 1212 1202 1219 1216	848 841 846 855 852
26 27 28 29 30 31			8.4 8.9 9.5 10.1 10.5 10.8	347 347 364 361 361 357	423 419 423 427 422 427	521 522 521 521 521 521	2230 2241 2248 2244 2242 2242	920 923 923 922 921 919	2117 2127 2134 2131 2129 2129	743 742 736 735 737 739	1733 1733 1736 1737 1736 1748	7751 7757 7755 7715 7687 7672	19.27 19.40 19.52 19.37 19.24 19.37	18.81 18.93 19.05 18.91 18.78 18.91	18.93 19.05 19.17 19.03 18.90 19.03	866 872 870 870 870 870	1220 1227 1194 1191 1184 1207	856 869 871 853 860 858
							Dissi	pation of	deposits	with JP-4	fuel							
32 33 34 35 36	100	0	0 7 11 17 22	334 339 334 334 334	427 427 428 427 424	517 519 521 519 520	2260 2255 2251 2235 2236	915 923 923 921 923	2143 2139 2135 2119 2120	730 767 772 775 779	1656 1693 1688 1679 1691	7803 7792 7799 7783 7797	19.69 19.65 19.64 19.41 19.31	19.21 19.17 19.17 18.92 18.83	19.34 19.29 19.29 19.04 18.95	1263 1274 1263 1255 1253	1229 1265 1278 1260 1262	820 867 866 855 864
37 38 39 40 41			30 36 45 52 59	332 334 334 335 339	427 427 427 427 427	520 520 520 520 520 521	2244 2247 2240 2237 2237	922 921 923 922 923	2128 2130 2124 2121 2121	790 794 791 796 792	1681 1684 1681 1686 1687	7799 7792 7803 7792 7794	19.63 19.63 19.63 19.63 19.61	19.17 19.16 19.16 19.16 19.14	19.29 19.28 19.28 19.28 19.26	1260 1263 1258 1258 1258	1293 1293 1289 1293 1281	878 883 879 885 883
42 43 44	 		62 67 77	342 341 335	427 427 427	522 519 520	2237 2240 2237	923 921 922	2121 2124 2121	795 795 795	1687 1687 1686	7797 7794 7794	19.59 19.65 19.63	19.12 19.18 19.16	19.24 19.30 19.28	1260 1263 1258	1276 1283 1293	885 890 885



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	Sta-	Instrumentation											
	tion	Static	Total	Total									
		pressure	pressure	temperature									
Engine inlet	1	8	24	12									
Compressor outlet	3	2	12	12									
Combustor outlet	4	_	8	16									
Exhaust-nozzle inlet	9		12	12									

Figure 1. - Schematic sketch of turbojet-engine installation.

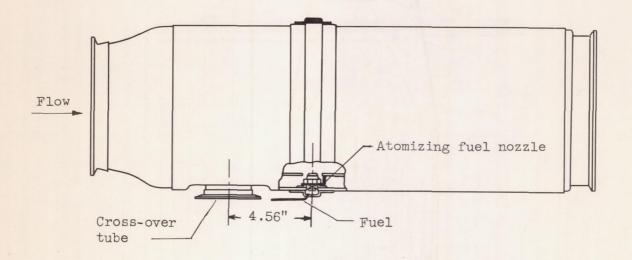
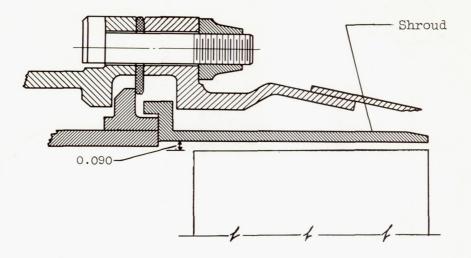
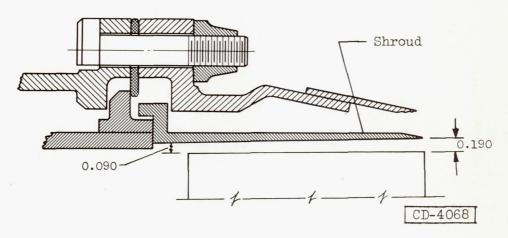


Figure 2. - Conical flow fuel nozzle installed in engine combustion chamber.



(a) Standard turbine shroud.



(b) Modified turbine shroud.

Figure 3. - Cross section of standard and modified turbine shroud.

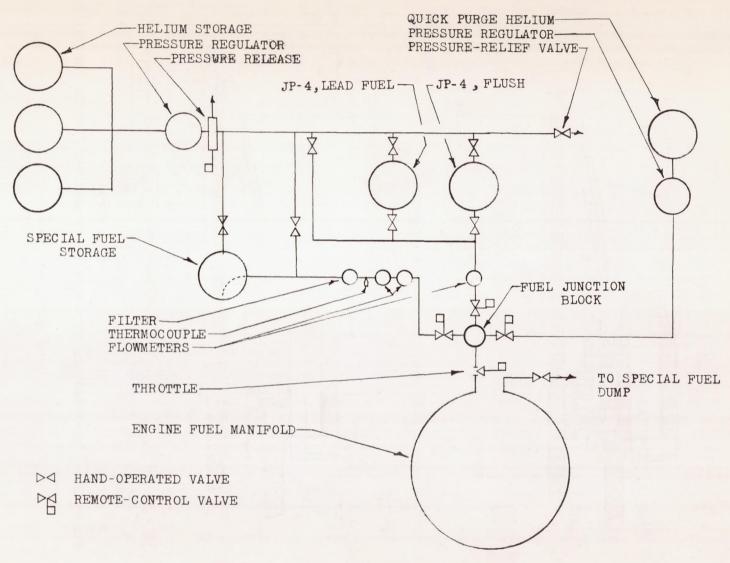
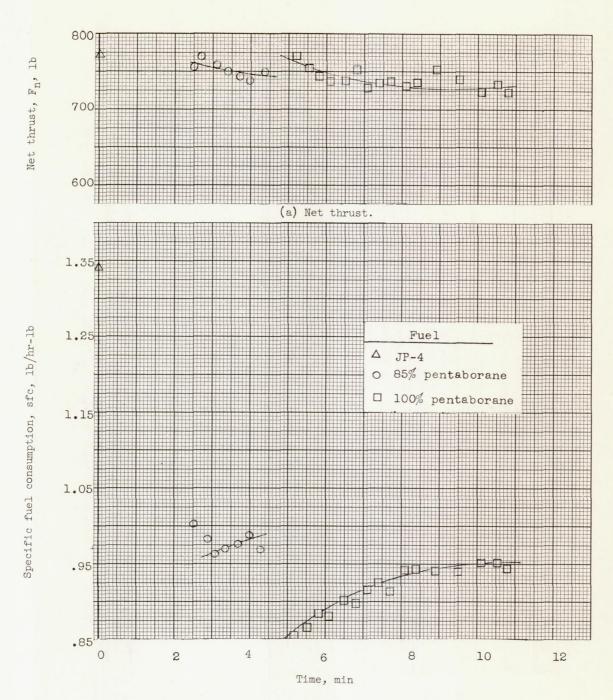


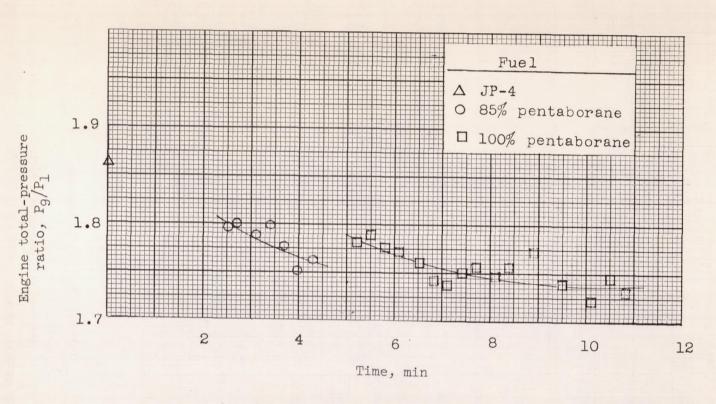
Figure 4. - Diagram of engine fuel system.





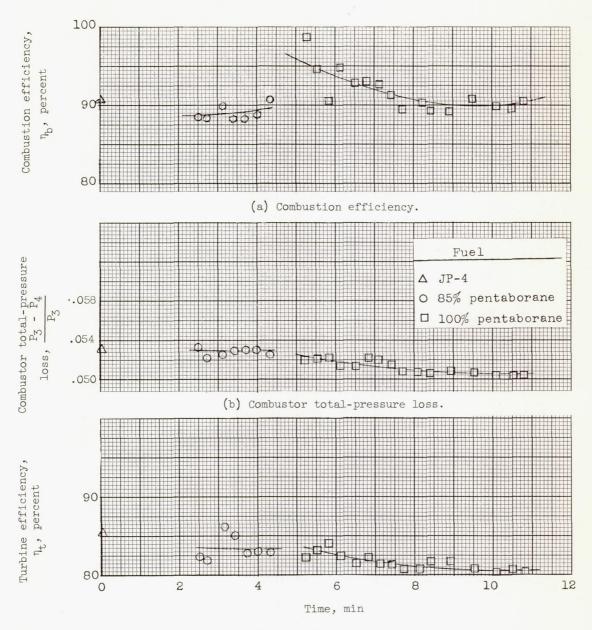
(b) Specific fuel consumption.

Figure 5. - Effect of operation with pentaborane fuels on turbojet-engine performance. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.



(c) Engine total-pressure ratio.

Figure 5. - Concluded. Effect of operation with pentaborane fuels on turbojet-engine performance. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.



(c) Turbine efficiency.

Figure 6. - Effect of operation with pentaborane fuel on turbojet-engine component performance. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.

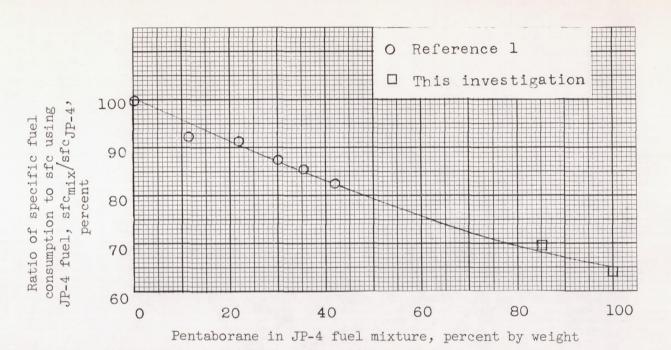
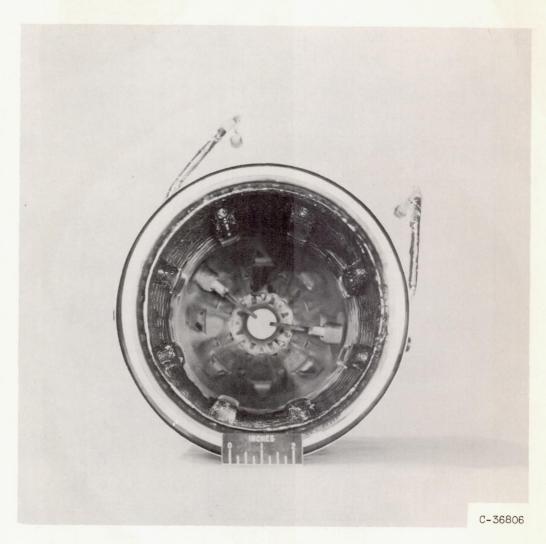
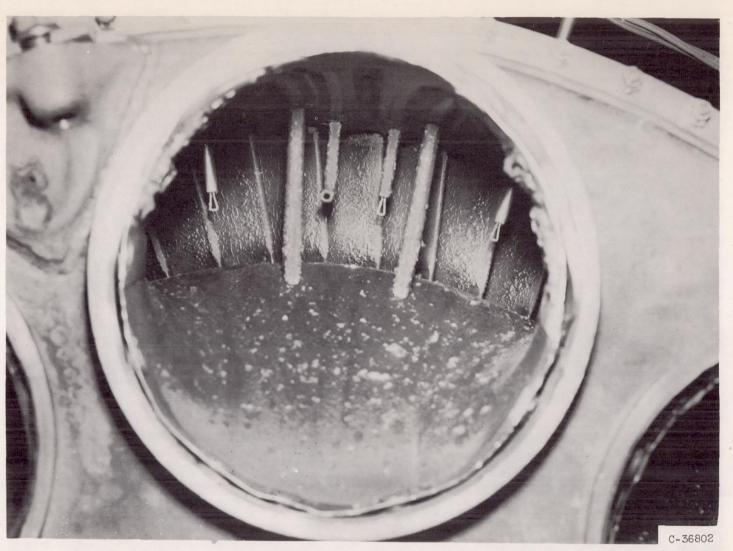


Figure 7. - Change in turbojet-engine specific fuel consumption with pentaborane concentration in hydrocarbon fuel mixture. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.



(a) Combustor.

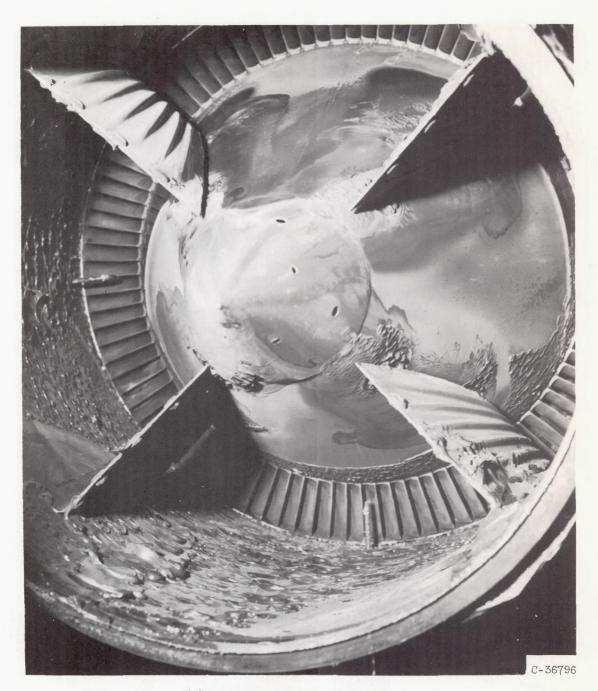
Figure 8. - Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.



(b) Combustor - turbine-inlet transition.

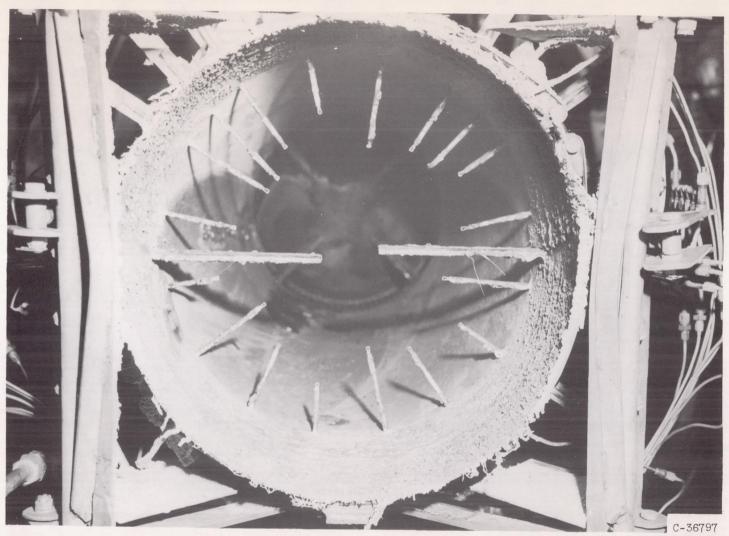
Figure 8. - Continued. Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.

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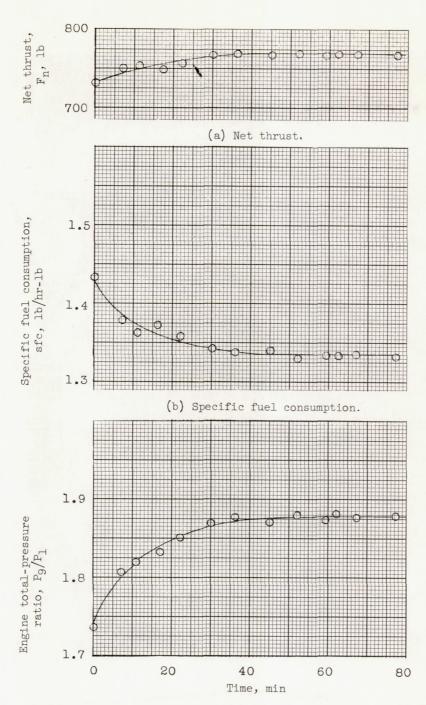
(c) Exhaust tail pipe and diffuser.

Figure 8. - Continued. Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.



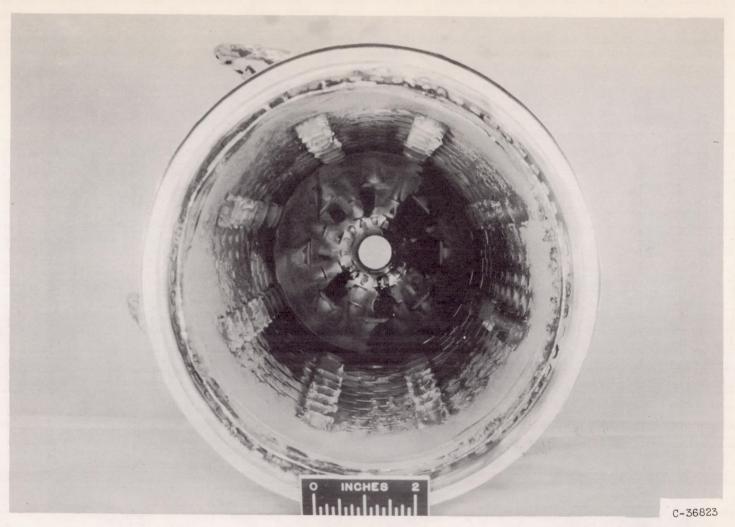
(d) Engine exhaust nozzle.

Figure 8. - Concluded. Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.



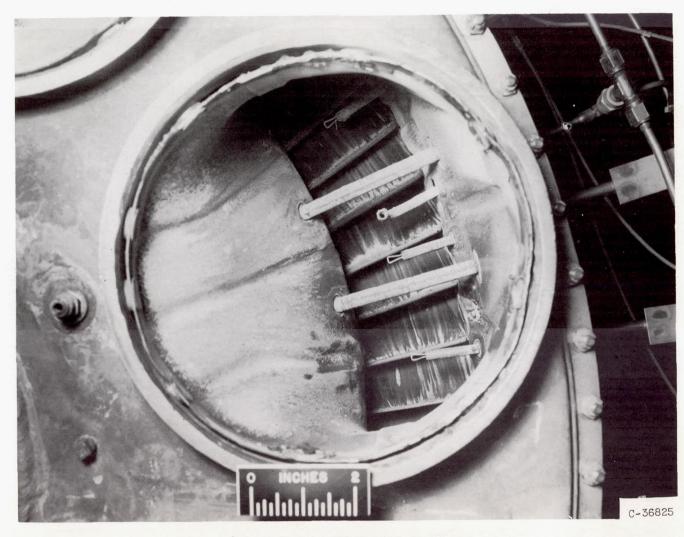
(c) Engine total-pressure ratio.

Figure 9. - Dissipation of boric oxide deposition in turbojet engine during operation with JP-4 fuel and return to normal performance operation. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.



(a) Combustor.

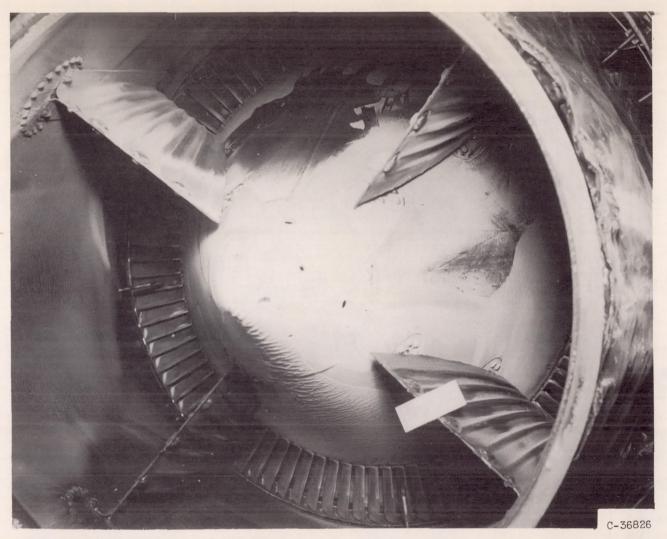
Figure 10. - Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.



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(b) Combustor - turbine-inlet transition.

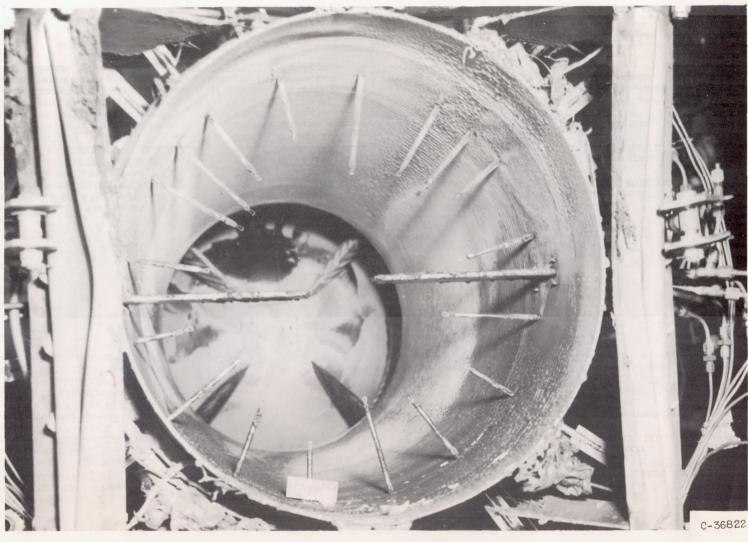
Figure 10. - Continued. Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.



(c) Exhaust tail pipe and diffuser.

Figure 10. - Continued. Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.

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(d) Engine exhaust nozzle.

Figure 10. - Concluded. Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.

CA - Langley Field,